Effects of pH and Cationic and Nonionic Surfactants on the Adsorption of Pharmaceuticals to a Natural Aquifer Material

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A wide range of pharmaceutical compounds have been identified in the environment, and their presence is a topic of growing concern, both for human and ecological health. Adsorption to aquifer materials and sediments is an important factor influencing the fate and transport of pharmaceutical compounds in the environment. Surfactants and other amphiphiles are known to influence the adsorption of many compounds and may be present in the environment from wastewaters or other sources. The work described here examines the adsorption of four pharmaceutical compounds, acetaminophen, carbamazepine, nalidixic acid, and norfloxacin, in the presence of a natural aquifer material. Adsorption was studied as a function of pH and in the presence and absence of two surfactants, cetylpyridinium chloride (CPC), a cationic surfactant, and Tergitol NP9, an ethoxylated nonionic surfactant. In the absence of surfactants, results indicate a 1−2 orders of magnitude variation in adsorption affinity with changing pH for each of the two quinolone pharmaceuticals (nalidixic acid and norfloxacin) but no measurable adsorption for carbamazepine or acetaminophen. In the presence of surfactants, adsorption of acetaminophen and carbamazepine was enhanced to extents consistent with compound hydrophobicity, while adsorption of nalidixic acid and norfloxacin was not. At high pH values, the anionic species of nalidixic acid exhibited enhanced adsorption in the presence of the cationic surfactant, CPC.

Introduction

A wide range of pharmaceuticals have been identified in the environment, including antibiotics, analgesics, psychiatric drugs, and natural and synthetic hormones (e.g., (*1−3*)). Human pharmaceuticals enter the environment through incomplete wastewater treatment of drugs either not absorbed by the body or intentionally discarded down the drain. Unused human pharmaceuticals may also enter the environment through landfill leachate. Veterinary pharmaceuticals in animal wastes enter the environment directly through infiltration into groundwater or runoff into surface waters. Although the concentrations of pharmaceuticals identified in the environment are typically low (often ranging from the ng/L to μg/L levels) (*2*), the potential for long-term risks to

human and ecological health are increasingly being recognized (e.g., (*2, 4−5*)). The presence of pharmaceuticals in the environment is a concern because of the potential for unintended effects on nontarget species and because long-term exposure to low, subtoxic concentrations may have unexpected consequences. In addition, many pharmaceuticals are not sufficiently removed by standard wastewater or water treatment procedures and so may present a risk to human health through contaminated drinking water (*2, 6−8*).

Because many pharmaceuticals exhibit complex speciation behaviors with varying pH, pharmaceutical interactions with aquifer materials and other compounds are likely to be highly pH-dependent. In addition, the performance of many pharmaceutical compounds in vivo may be strongly influenced by changing solution conditions, such as ionic strength, and by interactions with other compounds (e.g., (*9−15*)). As such, it is reasonable to hypothesize that all of these factors may influence the environmental behavior of many pharmaceuticals. Although the factors affecting adsorption of pharmaceuticals to environmental materials have been studied for several compounds (e.g., (*16−21*)), little work has been reported examining environmental interactions with amphiphilic compounds such as surfactants.

Surfactants and other amphiphiles are widely used in pharmaceutical products to stabilize emulsions and enhance drug delivery within the body (e.g., (*22−24*)). In addition, surfactants from detergents and other products are often present in wastewaters and enter the environment with pharmaceuticals through wastewater discharge (*25*). Although amphiphiles found in the environment are likely to be present at low concentrations, amphiphiles entering the environment with pharmaceuticals will likely be present at significantly higher concentrations than the pharmaceuticals themselves. Because surfactants can have a profound effect on the fate and transport of many contaminants (e.g., (*26−28*)), it was hypothesized that the same would be true of their effects on the fate and transport of pharmaceuticals.

The work described in this paper examines the influence of pH and surfactants on the adsorption of pharmaceuticals to a natural aquifer material. The objectives of the work were to determine the extent to which adsorption was influenced by varying pharmaceutical ionization state and aquifer material surface properties with varying pH, and the properties of the pharmaceuticals and surfactants studied.

Materials and Methods

Materials. The pharmaceutical compounds studied in this research were selected to represent a range of pharmaceutical classes and physical properties and were also selected because of their environmental relevance. The compounds selected were carbamazepine, an antiepileptic and an antidepressant; acetaminophen, an analgesic; nalidixic acid, a quinolone antibiotic; and norfloxacin, a fluoroquinolone antibiotic. Pharmaceutical compounds were purchased from Sigma-Aldrich, Co. (St. Louis, MO) and were used as received. Norfloxacin and nalidixic acid had stated minimum purities of 98%; acetaminophen and carbamazepine had stated minimum purities of 99%. Structures of these compounds are shown in Figure 1, and relevant properties are given in Table 1.

The surfactants used were Tergitol NP9 (Dow Chemical Company, Midland MI), an ethoxylated nonylphenol surfactant with an average of nine ethoxylate (EO) units per molecule, and cetylpyridinium chloride (CPC), a cationic surfactant. CPC was purchased from Sigma-Aldrich (St. Louis, MO), while NP9 was provided by Dow Chemical Company.

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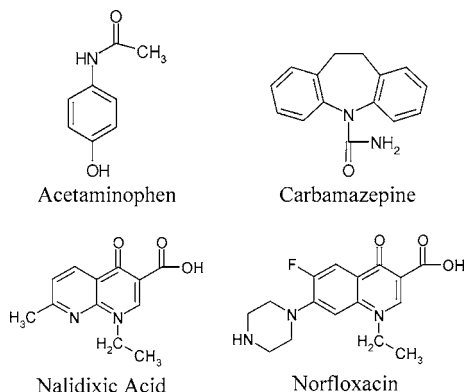
FIGURE 1. Structures of pharmaceutical compounds used. Neutral forms of nalidixic acid and norfloxacin shown.

TABLE 1. Properties of Pharmaceutical Compounds Used

compound	MW (g/mol)	solubility (mg/L)	log K_{ow}	pK_a values
acetaminophen	151.16	12 900[a]	0.46[b]	9.38[c]
carbamazepine	236.27	121[a]	2.45[d]	n/a
nalidixic acid	232.24	33[e] (pH 5)	1.54[f] (pH 5)	5.95[e]
		328[e] (pH 7)	0.47[f] (pH 7)	
		27 600[e] (pH 9)	−1.16[f] (pH 9)	
norfloxacin	319.33	161 000[e] (pH 5)	−1.24[f] (pH 5)	6.3, 8.38[e]
		400[e] (pH 7)	−1.09[f] (pH 7)	
		910[e] (pH 9)	−1.56[f] (pH 9)	

[a]Reference (44). [b]Reference (30). [c]Reference (45). [d]Reference (46). [e]Reference (10). [f]Reference (35).

CPC had a minimum stated purity of 99%. NP9 is a commercial ethoxylated surfactant with greater than 99% active content. Like most ethoxylated surfactants, NP9 contains a broad distribution of ethoxylated components which results from the manufacturing process. Both surfactants were used as received. Nonionic and cationic surfactants were selected for this research because of their high adsorption affinity for soils and aquifer materials; it was hypothesized that surfactants with the ability to substantially modify solid surfaces would be most likely to influence the migration of pharmaceutical compounds. An additional reason for studying NP9 is that many of the biodegradation products of ethoxylated alkylphenol surfactants such as NP9 are suspected endocrine disrupters (29−30).

All adsorption experiments were conducted using Canadian River alluvium (CRA). CRA was collected from the alluvial channel of the Canadian River in Norman, Oklahoma. CRA was sieved to different size fractions and washed to minimize fines. Adsorption experiments used to evaluate pharmaceutical adsorption were conducted using 80−140 mesh CRA. The organic carbon content of unsieved CRA has previously been measured to be 0.44% (31); on the basis of previous analyses of specific subfractions of CRA, the organic content of the sieved material used for this work is likely as much as an order of magnitude lower (31). CRA was characterized using X-ray diffraction (XRD), scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS), and quantitative image analysis of optical microscope images. Results indicated that although the material was predominantly a quartz sand, up to a third of the grains exhibited modest iron oxide coatings. Individual grains of alkali and plagioclase feldspars, amphiboles, cordierite, ilmenite, magnetite, and tourmaline were detected in a cumulative amount less than 1−2% of the total. Selected grains also showed traces of attached clay minerals, although because the material was sieved and washed, unassociated clay was not present in measurable quantities.

Methods. A Shimadzu (Columbia, MD) UV 1601 spectrophotometer was used for all analyses in batch experiments. For all experiments, full UV absorbance spectra were recorded for each sample and standard. For carbamazepine and acetaminophen, spectra were recorded between wavelengths of 200 and 300 nm at 0.2-nm intervals. For the two quinolone antibiotics, each of which has a significant absorbance peak above 300 nm, spectra were recorded between wavelengths of 200 and 400 nm at 0.5-nm intervals.

A multiwavelength analysis method was then used to determine the concentration in solution. The method involved use of 250−300 separate linear standard curves for each compound in solution, covering a subset of scanned wavelengths where UV absorbance was observed (each standard curve corresponded to an individual wavelength and was arranged to calculate absorbance as a function of concentration). Total absorbance in samples at each wavelength was taken to be the sum of absorbance from each compound (pharmaceutical, surfactant, soil blank) in solution. A predicted total spectrum was generated for each sample by applying standard curves to hypothetical concentrations of each component and summing the resulting absorbances. The solver function in Microsoft Excel was used to adjust hypothetical concentrations of components until the error between predicted and sample spectra was minimized. For all experiments presented here, fits were excellent, with visually near-exact agreement between predicted and sample spectra for the range of wavelengths fit. The method allowed multiple compounds to be determined simultaneously (including multiple pH-dependent species of each pharmaceutical in many cases and surfactants) and was highly insensitive to variation in fines dispersion caused by surfactants (a common difficulty using single wavelength UV-absorbance measurements). An additional benefit of the method is that complexation interactions of pharmaceutical compounds can lead to a spectral shift in absorbance and fluorescence spectra (e.g., (14, 32)), potentially providing clues to adsorption behavior in different systems.

Adsorption experiments were conducted in 16-mL glass vials with Teflon-lined caps. Samples were prepared by adding 8 mL of pharmaceutical solution (containing one pharmaceutical compound, 0.01 M CaCl₂ to mimic background groundwater ionic strength and to reduce dispersion of fines, and in selected experiments one surfactant) to approximately 3 g of soil (weighed for each sample). The pH was controlled by addition of 0.02 M NaOH or HCl in varying amounts in original sample recipes. Samples were equilibrated by end-over-end rotation for at least 48 h. Samples were then centrifuged, and the supernatant was analyzed for pharmaceutical and surfactant concentrations, and the pH was measured using an Acumet (Fisher Scientific, Hampton, NH) gel-filled combination pH electrode and Acumet AB-15 pH meter. Single-point adsorption experiments, used to determine K_D values, were conducted using initial concentrations between 11 and 12 mg/L. Although these concentrations (and the initial concentrations used in isotherm experiments, which ranged up to approximately 12 mg/L) are higher than likely environmental concentrations of pharmaceuticals, except directly near a contamination source, practical aspects of laboratory adsorption measurements necessitated use of the higher concentrations. Although field measurements of pharmaceutical concentrations often involve extraction techniques to concentrate many liters of water for analysis, this approach is difficult to apply to measurement of adsorption because of the large sample sizes needed and problems of error propagation. As such, for this study it was determined that accurate measurement of adsorption behavior was the primary objective and an important first step in understanding the effects of surfactants on pharmaceutical adsorption in the environment.
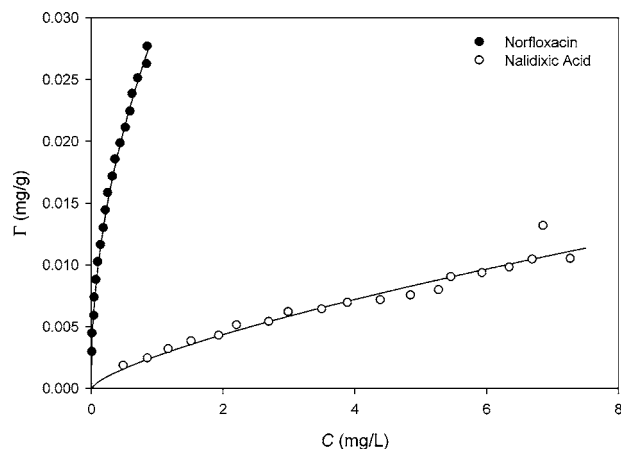
FIGURE 2. Adsorption isotherms of norfloxacin and nalidixic acid (pH = 7.6 ± 0.17). Freundlich isotherm fits shown: norfloxacin Γ = 0.0293 $C^{0.49}$ mg/g; nalidixic acid Γ = 0.00263 $C^{0.73}$ mg/g.

Results and Discussion

As can be seen from the properties in Table 1, the selected pharmaceutical compounds have a wide range of properties, from the moderately hydrophobic carbamazepine to the very hydrophilic acetaminophen. The two quinolone pharmaceuticals have properties that vary widely with pH, and the speciation of quinolones and fluoroquinolones with pH has a strong effect on their performance. While nalidixic acid has a single pK_a (5.95 (*10*)), corresponding to ionization of the carboxylic acid group, fluoroquinolones, such as norfloxacin, have two pK_a values within environmentally relevant ranges (typ. ~6−7 and ~8−9) and can be positively charged, negatively charged, zwitterionic, or uncharged (each pK_a is actually a composite of micro-pK values corresponding to equilibria between the four species (*10, 33−34*) (*10*). Within environmentally relevant pH ranges, it is common for two or more species of a particular compound to be present in significant quantities. Interactions with other compounds can be strongly pH dependent, and quinolones and fluoroquinolones complex strongly with many different cations, influencing their solubility behavior, in vivo bioavailability, and lipophilicity in different pH ranges (*12−14, 32*). The salts of fluoroquinolones can also influence their solubility at lower pH values (*10*). As is apparent from Table 1, nalidixic acid is most hydrophobic at low pH, exhibiting a high log K_{ow} and low solubility. Norfloxacin is most hydrophobic at pH values between its two pK_a values; correspondingly, norfloxacin would be expected to have the highest in vivo biological activity at intermediate pH values (*33, 35−36*).

Figure 2 shows adsorption isotherms for nalidixic acid and norfloxacin on Canadian River Alluvium (CRA) at pH 7.6 ± 0.17. Although both isotherms are observed to be nonlinear, the norfloxacin has a greater degree of nonlinearity, with a Freundlich exponent of 0.49, compared with 0.73 for the nalidixic acid. The nonlinearity of the isotherms likely results from adsorption to heterogeneous CRA surfaces (e.g., (*37*)), and the difference between the nonlinearity of the isotherms is likely due to the difference in the adsorption mechanisms which leads to different adsorption affinities for specific surface moieties. Although norfloxacin is present in anionic, neutral (zwitterionic or uncharged), and cationic species at significant fractions at this pH (which is near the isoelectric point for the molecule), the bulk of the adsorption likely results from charge−charge interactions between the cationic and zwitterionic species of norfloxacin and the negatively charged quartz sand surface. In contrast, the adsorption of nalidixic acid at this pH is likely the result of hydrophobic interactions between the uncharged species and the surface, as the anionic species of nalidixic acid is unlikely to adsorb.
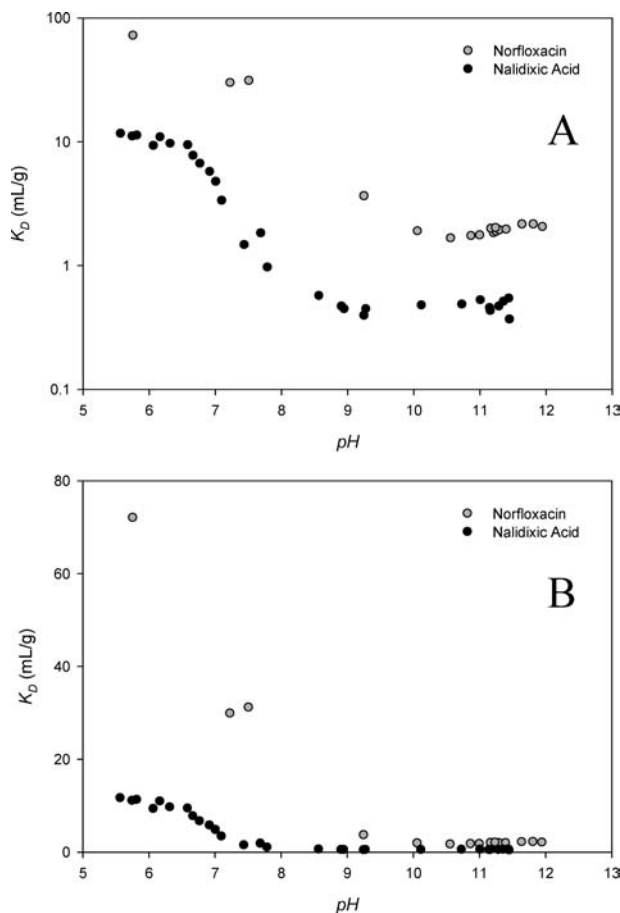
FIGURE 3. K_D vs pH for norfloxacin and nalidixic acid. K_D is shown in logarithmic (A) and linear (B) scales.

Both the low fraction of uncharged nalidixic acid species present at pH 7.6 (approximately 2%) and the difference in adsorption strength of the two adsorption mechanisms likely explain the considerably stronger affinity of norfloxacin for the surface. Adsorption measurements of both acetaminophen and carbamazepine at this pH found adsorption to be too low to measure with the methods used (corresponding to a linear adsorption coefficient, K_D, less than approximately 10^{-2} mL/g). While it is not surprising that acetaminophen did not adsorb to a measurable extent, given its very high water solubility and low reported log K_{ow} (Table 1), at least modest adsorption of carbamazepine might have been expected, given its relatively low solubility and moderately high log K_{ow} value (Table 1). Comparison between the observed adsorption behavior and the solubility and log K_{ow} values for carbamazepine, norfloxacin, and nalidixic acid makes it clear that molecule hydrophobicity does not provide a good indicator of the relative adsorption of the compounds studied here.

To examine the effect of varying pH and speciation on adsorption, a wide range of single-point adsorption measurements were conducted and corresponding K_D values were calculated ($K_D = \Gamma/C$). Although use of a single K_D value implies a linear isotherm, it was determined that use of single-point measurement was warranted as it would allow the greatest range of experiments to be conducted, providing a considerable quantity of information about the behavior of pharmaceutical compounds under varying conditions, despite the nonlinearity seen in the isotherms in Figure 2. Figures 3A and 3B show K_D values as a function of pH for nalidixic acid and norfloxacin for the pH range covering approximately 5.5−12. From Figure 3A, for which the vertical axis is a logarithmic scale, it is apparent that adsorption

TABLE 2. Approximate Retardation Factors ($R = 1 + (\rho_b K_D/n)$) Corresponding to K_D Values[a]

K_D (mL/g)	R
100	415
50	208
20	83.9
10	42.4
5	21.7
2	9.29
1	5.14
0.5	3.07
0.2	1.83
0.1	1.41
0.05	1.21
0.02	1.08
0.01	1.04

[a]Calculation based on a porosity (n) of 0.39 and a solid density (ρ_s) of 2.65 g/cm^3 ($\rho_b = (1 - n)\rho_s$). Actual R values would vary slightly due to variations in n and ρ_b with actual packing.

FIGURE 4. Adsorption isotherms of CPC and NP9 surfactants (pH $= 7.1 \pm 0.13$). Dashed line indicates approximate surfactant surface coverage corresponding to subsequent pharmaceutical adsorption experiments.

affinity of norfloxacin is approximately 5 times greater than the adsorption affinity of nalidixic acid over the entire pH range, and both compounds follow the same trend with varying pH. For reference, approximate retardation coefficient ($R = 1 + \rho_b K_D/n$) values corresponding to linear isotherms with the range of K_D values observed are shown in Table 2. Comparison between Table 2 and the K_D values in Figure 3A indicates that transport of both nalidixic acid and norfloxacin would be expected to be retarded to a measurable extent over the entire pH range examined. At high pH values, nalidixic acid transport would be expected to be retarded by a factor of approximately 3 when compared with a conservative tracer (i.e., $R \approx 3$), while norfloxacin would be expected to be retarded by a factor of approximately 8 (i.e., $R \approx 8$). At lower pH, near pK_{a1} for both compounds, nalidixic acid and norfloxacin would be expected to be retarded by factors of approximately 40 and 290, respectively.

The trends with varying pH observed in Figure 3 are consistent with the speciation of the two compounds; both compounds are anionic at high pH and would be expected to adsorb weakly to a negatively charged, low-carbon aquifer material such as CRA. In the case of nalidixic acid, as pH decreases, the quantity of uncharged species increases, increasing the opportunities for hydrophobic interaction with the surface. From Figure 3B (which has a linear vertical axis), it is apparent that the adsorption of nalidixic acid begins to increase substantially as pH drops below pH $\sim$ 7, approximately one pH unit above the pK_a of the compound. In the case of norfloxacin, adsorption begins to increase substantially as pH drops below pH $\sim$ 9.5, approximately one pH unit above pK_{a2} for the compound, suggesting that the zwitterionic norfloxacin species plays a significant role in adsorption. Measurements of adsorption below pH $\sim$ 5.5 for the norfloxacin found adsorption affinity to be too high to measure with the experimental conditions used, suggesting extremely strong adsorption of the cationic species of norfloxacin. Measurements of adsorption below pH $\sim$ 5.5 for the nalidixic acid were complicated by a 4-nm blue-shift in the nalidixic acid spectrum for the samples (but not the standards at the same pH), suggesting complexation may have been occurring with some component dissolving from the CRA. Additional research is necessary to determine the nature of the complexation interaction. However, on the basis of the size of the peaks, it appears that adsorption of nalidixic acid may remain approximately constant below pH 5.5.

To examine the effects of surfactants on the adsorption of pharmaceutical compounds, one cationic surfactant and one nonionic surfactant were selected. Cationic and nonionic surfactants were selected for this work because of their strong
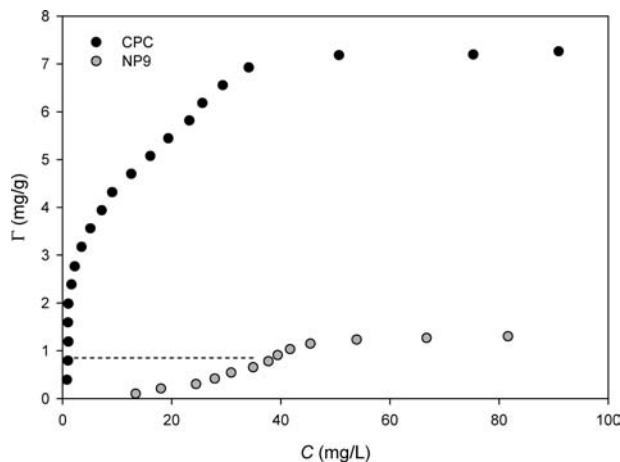
affinity for many natural aquifer materials (e.g., (27, 38–40)). It was hypothesized that a surfactant that would modify soil surface properties would also influence the adsorption of pharmaceutical compounds. Figure 4 shows adsorption isotherms for cetylpyridinium chloride (CPC), a cationic surfactant, and Tergitol NP9, an ethoxylated nonionic surfactant with an average of nine ethoxylate (EO) units. Comparison between the vertical axes of Figures 2 and 4 shows that the adsorption of both surfactants (Figure 4) is up to 2–3 orders of magnitude greater than the adsorption of nalidixic acid or norfloxacin under the same conditions. CPC, in particular, adsorbs very strongly at low concentrations because of the charge–charge interaction between the cationic CPC monomers and the anionic quartz sand surface. However, adsorption of NP9 is still quite substantial, resulting from hydrogen bonding with the surface and surface-aggregate formation as concentration increases. Both surfactant isotherms are typical of isotherms for surfactants on mineral-dominated surfaces, in that they exhibit a break in slope as surfactant aggregates form on the solid surface and plateau near the surfactant critical micelle concentration (CMC; approximately 40 mg/L and 50 mg/L at this ionic strength for CPC and NP9, respectively) as the formation of micelles limits the concentration of monomers in solution (e.g., (27, 38–41)). Approximate surfactant adsorption levels used for subsequent pharmaceutical adsorption experiments are indicated in Figure 4 and correspond to surface coverages of 0.99 mg/g ($f_{oc}* = 7.3 \times 10^{-4}$, where $f_{oc}*$ is the fraction of organic carbon content based on surfactant alone) for CPC and 0.82 mg/g ($f_{oc}* = 5.3 \times 10^{-4}$) for NP9. These coverages were selected to be similar between the two surfactants and to correspond to equilibrium solution concentrations below the surfactant CMCs to prevent micellar solubilization from influencing results. Although these surfactant surface coverages are likely higher than might be anticipated in environmental systems, they were selected as a first step in understanding the mechanisms through which surfactants may influence pharmaceutical adsorption.

Figures 5 and 6 show the effects of CPC and NP9 on adsorption of norfloxacin and nalidixic acid, respectively. From the two figures, it is apparent that neither compound's adsorption is influenced to any measurable extent by the presence of NP9. This suggests that partitioning interactions with adsorbed surfactant aggregates are likely not major factors in the adsorption of nalidixic acid and norfloxacin in the presence of surfactant. This result is consistent with solubilization studies conducted with nalidixic acid and NP9 as a part of this work, which found no measurable solubi-
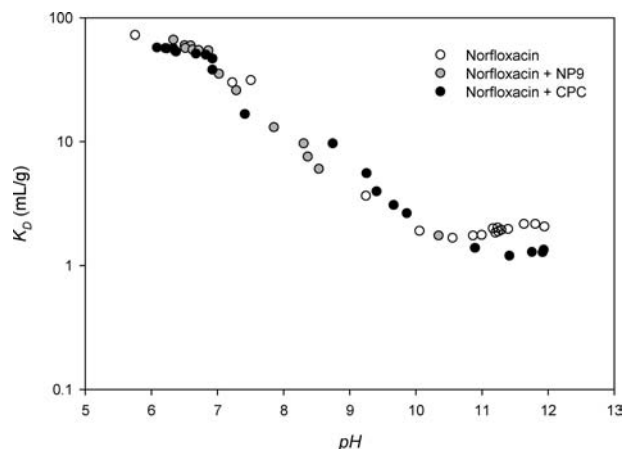
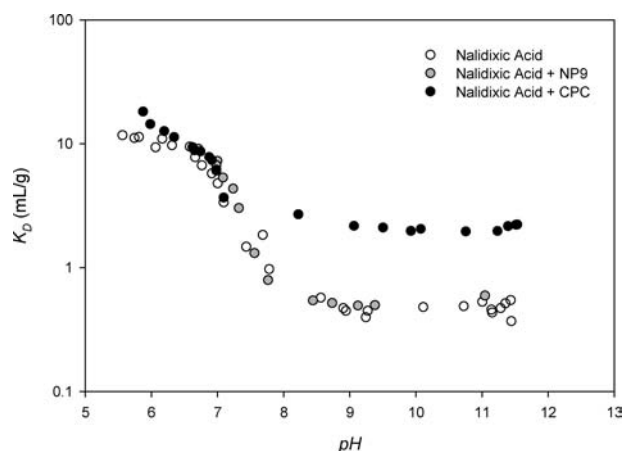**FIGURE 5.** K_D vs pH for norfloxacin in the presence and absence of surfactants.

FIGURE 6. K_D vs pH for nalidixic acid in the presence and absence of surfactants.

lization of either nalidixic acid species (uncharged or anionic) by NP9 micelles (data not shown). From Figure 5, it is also apparent that CPC has no measurable effect on the adsorption of norfloxacin. However, from Figure 6, it is apparent that CPC causes a considerable increase in the adsorption of nalidixic acid at higher pH values, producing a 4-fold increase in K_D from approximately 0.5 to 2 mL/g, corresponding to an increase in the retardation coefficient from ~3 to ~9 (Table 2). A possible explanation for the increased adsorption of nalidixic acid in the presence of CPC is that ion pairing between the anionic nalidixic acid species (the predominant species at high pH) and cationic CPC monomers may be reducing the solubility of the nalidixic acid, thereby increasing the driving force for adsorption.

The reason for the difference between the effects of CPC on nalidixic acid and norfloxacin adsorption is unknown, but it is possible that the difference is due to differences in the strength of ion pairs formed by the two pharmaceuticals with CPC and the ability of the ion pairs to interact with the solid surface or the adsorbed surfactant layer. One study of the effects of cetyltrimethylammonium bromide (CTAB, a cationic surfactant similar to CPC) on reverse-phase HPLC (high-performance liquid chromatography) separation of quinolones (42) found widely varying effects of CTAB ion pairing on the HPLC retention of different quinolones, with nalidixic acid exhibiting a factor of 8 increase in HPLC retention in the presence of CTAB at pH 8, compared with a factor of 2 increase in retention for norfloxacin at the same pH. Although the different speciation of the two compounds at pH 8 makes quantitative conclusions about ion pair adsorption affinities difficult, the same study also examined
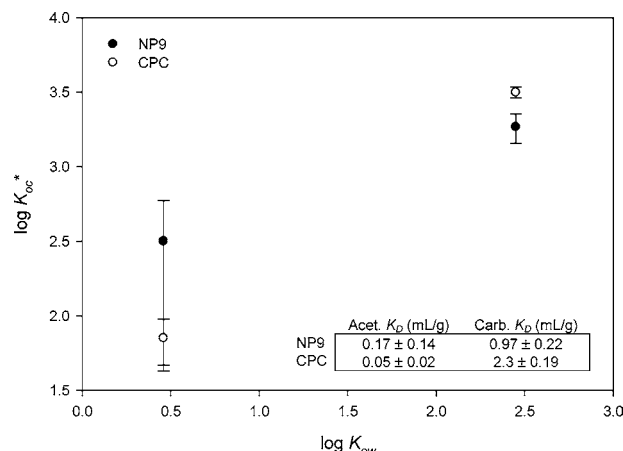
FIGURE 7. Normalized adsorption (log K_{oc}*) of acetaminophen and carbamazepine in the presence of surfactants, shown as a function of pharmaceutical log K_{ow} values. Error bars indicate sample estimate of standard deviation on the basis of 14 samples per pharmaceutical/surfactant combination.

n-acetylnorfloxacin, a derivatized version of norfloxacin with a single pK_a at 6.03 (34) and similar speciation to nalidixic acid (i.e., uncharged and anionic species only). Results indicated that HPLC retention of n-acetylnorfloxacin was increased by a factor of 3 in the presence of CTAB, less than 40% of the increase observed for nalidixic acid, suggesting that ion pairs between a cationic surfactant and anionic norfloxacin species might be expected to have a lower adsorption affinity than ion pairs between a cationic surfactant and anionic nalidixic acid species.

Figure 7 shows the effects of NP9 and CPC on the adsorption of acetaminophen and carbamazepine. Adsorption measurements with acetaminophen and carbamazepine were conducted between pH 6 and 9 for acetaminophen and pH 6 and 11 for carbamazepine. Because neither acetaminophen nor carbamazepine have pK_a values within these pH ranges, the order-of-magnitude effects observed for nalidixic acid and norfloxacin with changing pH would not be expected and were not observed. As such, the K_D values given in Figure 7 are averages of 14 measurements for each pharmaceutical/surfactant combination over each pH range studied. Figure 7 shows log K_{oc}* (defined as the organic carbon-normalized adsorption coefficient calculated on the basis of organic carbon due to surfactant alone (K_{oc}* = K_D/f_{oc}*)) plotted as a function of log K_{ow} for the two pharmaceutical compounds in the presence of surfactant. The fact that adsorption of these compounds was too low for measurement in the absence of surfactant indicates that these compounds had little adsorption affinity for the natural organic carbon present in the CRA. The substantial increase in adsorption in the presence of surfactants is consistent with the observation that compounds often exhibit affinities for adsorbed surfactant aggregates that are orders of magnitude stronger than affinities for natural organic matter on a mass basis (e.g., (27)).

In the case of acetaminophen, K_D values increase to approximately 0.17 mL/g in the presence of NP9 and to 0.05 mL/g in the presence of CPC, both values corresponding to small but observable retardation coefficients ($R \approx 1.2$ in the presence of CPC, $R \approx 1.8$ in the presence of NP9). In the case of carbamazepine, K_D values increase to approximately 0.97 mL/g in the presence of NP9 and to 2.3 mL/g in the presence of CPC, corresponding to retardation coefficients of approximately $R \approx 4.7$ in the case of NP9, and $R \approx 13.4$ in the case of CPC, both values likely to significantly retard the transport of carbamazepine.

The greater adsorption of carbamazepine versus acetaminophen when surfactant is present is consistent with

the hydrophobic nature of carbamazepine (lower solubility and higher log K_{ow} compared with acetaminophen). Although hydrophobic interactions between different compound classes and different surfactant adsorbed layers would not be expected to exhibit the same quantitative behavior (just as published relationships between log K_{oc} and log K_{ow} can vary greatly between organic matter with different properties (e.g., (43))), it is apparent from Figure 7 that the more hydrophobic carbamazepine interacts more strongly with the adsorbed layers of both surfactants.

Significance for Environmental Fate of Pharmaceuticals. The results of this work indicate that cationic and nonionic surfactants can influence the adsorption and transport of pharmaceutical compounds, potentially reducing the rate of their migration through the subsurface. However, the effects of surfactants observed in this study differed between pharmaceutical compounds, with acetaminophen and carbamazepine exhibiting behavior consistent with partitioning to adsorbed surfactant aggregates, but the quinolones (nalidixic acid and norfloxacin) exhibiting little hydrophobic interaction with adsorbed surfactant, even at pH values for which uncharged pharmaceutical species would be expected to be present. Just as hydrophobicity (e.g., high log K_{ow}, low solubility) is not necessarily a good indicator of pharmaceutical adsorption, it is also not necessarily a good indicator of the effects of surfactants or other amphiphiles on pharmaceutical transport, and a priori predictions made on the basis of hydrophobicity are likely to be unsatisfactory.

An important question that remains from this work is the effect of concentration on adsorption of pharmaceuticals in the presence of surfactants. Ongoing work is exploring techniques of conducting batch adsorption studies at lower concentrations of both pharmaceuticals and surfactants. The question that remains, however, is to what extent would the same pharmaceutical adsorption behaviors be observed at lower surfactant and pharmaceutical concentrations? It is likely the answer will depend on the mechanisms involved, with ion pairing or complexation interactions playing an important role even at very low surfactant and pharmaceutical concentrations, but hydrophobic interactions with adsorbed surfactant layers requiring higher surfactant concentrations where surface aggregates may be present.

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